Ridges and Soft Jet Components in Untriggered Di-hadron Correlations in Pb+Pb Collisions at 2.76 TeV

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We study untriggered di-hadron correlations in Pb+Pb at 2.76 TeV, based on an event-by-event simulation of a hydrodynamic expansion starting from flux tube initial conditions. The correlation function shows interesting structures as a function of the pseudorapidity difference $\Delta\eta$ and the azimuthal angle difference $\Delta\phi$, in particular comparing different centralities. We can clearly identify a peak-like nearside structure associated with very low momentum components of jets for peripheral collisions, which disappears towards central collisions. On the other hand, a very broad ridge structure from asymmetric flow seen at central collisions, gets smaller and finally disappears towards peripheral collisions.

Two-dimensional di-hadron correlations provide a wealth of information about the reaction dynamics of heavy ion collisions and proton-proton scatterings. Experimental results have been obtained for Au+Au collisions at 200 GeV[1, 3, 4] and for proton-proton reactions at 7 TeV [5], results for Pb+Pb will appear soon. Whereas in most applications momentum triggers are employed, we will discuss in this letter untriggered correlations, dominated by very low momentum pairs. Also here, one observes a nearside ridge-like structure extended over many units in $\Delta\eta$. In this letter, we will discuss the centrality dependence of the two-dimensional di-hadron correlation function in Pb+Pb collisions at 2.76 TeV.

We employ a sophisticated hydrodynamical scenario (for details see [6]), with initial conditions obtained from a flux tube approach (EPOS), compatible with the string model, used since many years for elementary collisions (electron-positron, proton proton), and the color glass condensate picture [7]. The equation-of-state is compatible with lattice gauge results of ref. [8]. We use a hadronic cascade procedure after hadronization from the thermal system at an early stage [10, 11].

For the present discussion it is important to note that we perform event-by-event simulations, taking into account the highly irregular space structure of single events, as shown in fig. 1. There are a couple of "hot spots" visible, which have actually a long range structure in longitudinal direction (a very similar picture is obtained for different values of η_s (longitudinal translational invariance)). The irregular structure of the initial energy density translates in an irregular transverse flow some time later, as seen in fig. 2. One can easily see that the two remarkable peaks in the lower half of the transverse plane in fig. 1 squeeze matter outwards with large velocity just in between them, see fig. 2.

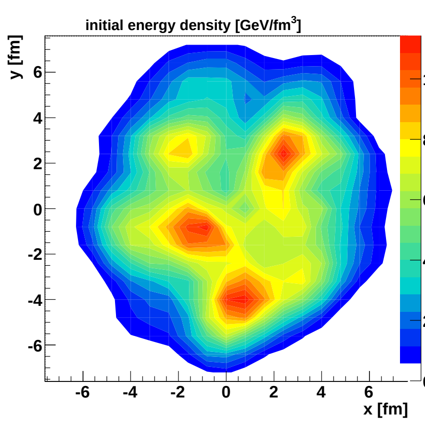

Figure **1**: Initial energy density as a function of the transverse coordinates, at space-time rapidity $\eta_s = 0$.

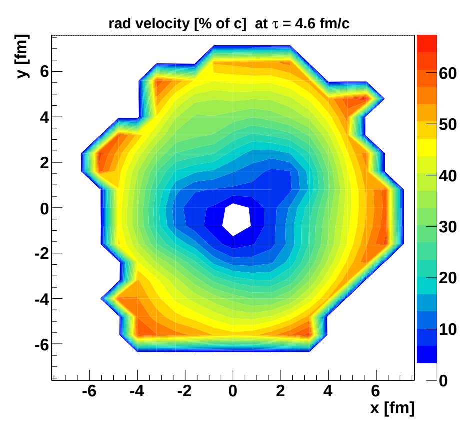

Figure **2**: Radial flow velocity (in % of c) as a function of the transverse coordinates, at space-time rapidity $\eta_s = 0$, at $\tau = 4.6\,\mathrm{fm/c}$.

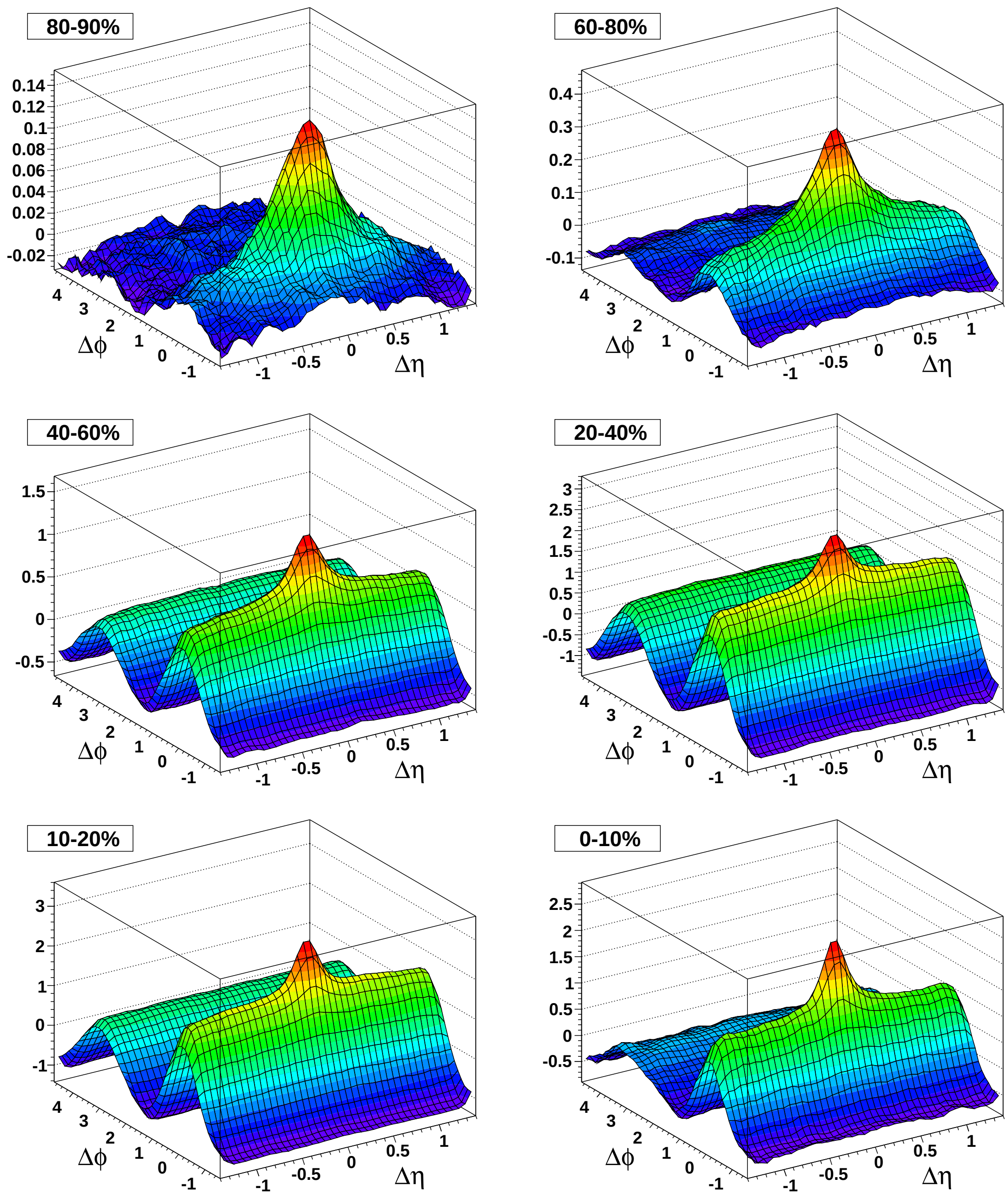

Figure **3**: (Color online) Untriggered di-hadron correlation function $R(\Delta\eta, \Delta\phi)$ including Bose-Einstein statistics versus $\Delta\eta$ and $\Delta\phi$ for different centralities.

Based on the the above scenario, we compute the two-dimensional di-hadron correlations function R as a function of the pseudorapidity difference $\Delta\eta$ and the azimuthal angle difference $\Delta\phi$. We use $R = C\,(\rho_{\mathrm{real}}/\rho_{\mathrm{mixed}} - 1)$, with a normalization $C = N/(2\pi\Delta)$, where N is the multiplicity and $\Delta$the pseudorapidity range. We show in fig. 3 the results for different centralities, using a full calculation, including Bose-Einstein statistics (for $\pi^+\pi^+$ and $\pi^-\pi^-$pairs), and in fig. 4 the corresponding results without Bose-Einstein statistics. After removing the Bose-Einstein peak (in our case making the calculation without Bose-Einstein statistics, see fig. 4)

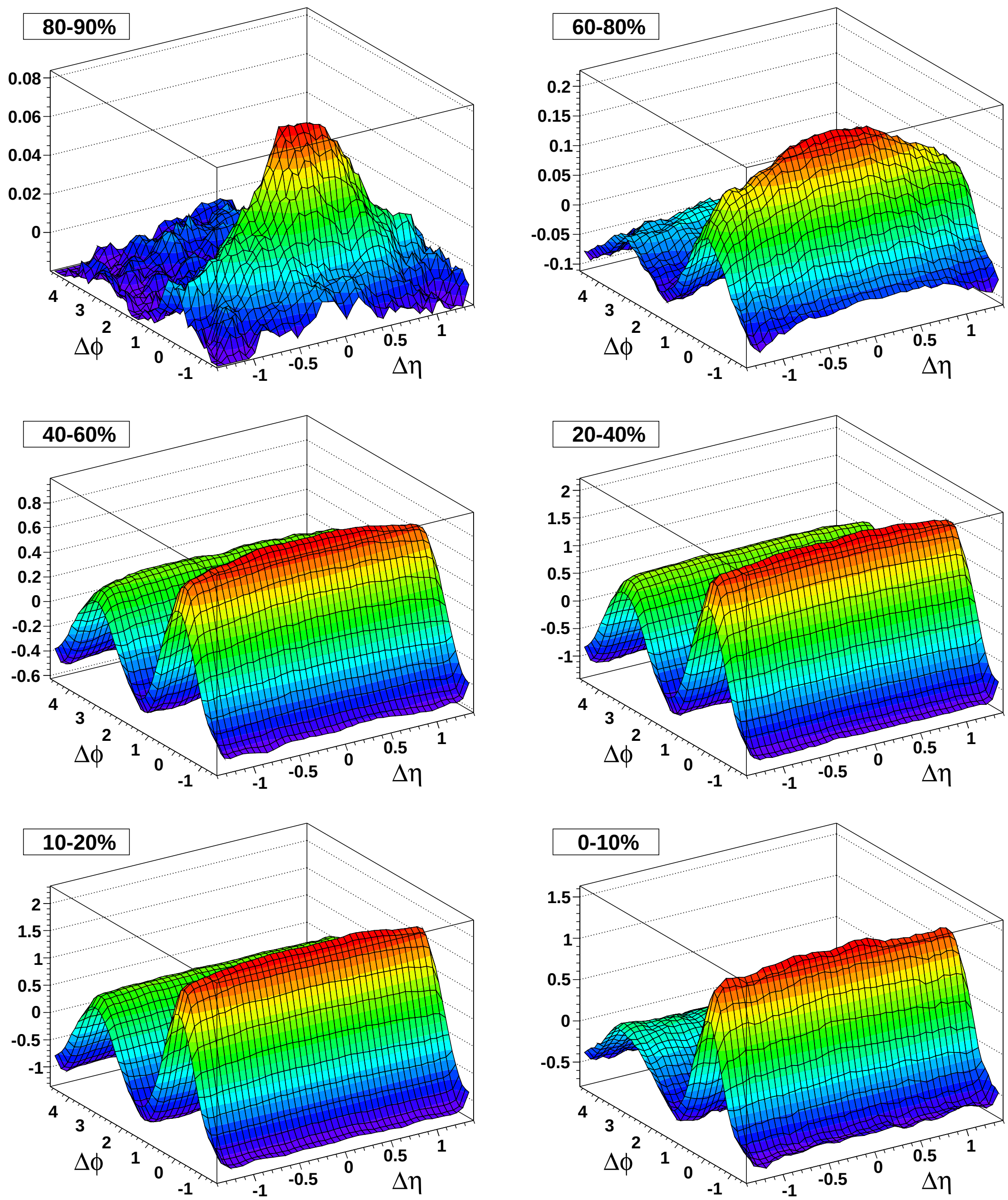

Figure 4: (Color online) Untriggered di-hadron correlation function $R(\Delta\eta, \Delta\phi)$ without Bose-Einstein statistics versus $\Delta\eta$ and $\Delta\phi$ for different centralities.

there are three structures visible:

- The elliptical flow of the form $\cos(2\Delta\phi)$, strongest at intermediate centralities, but also present for central collisions.
- A very broad ridge at $\Delta\phi = 0$, which gets smaller towards more peripheral collisions, and disappears for the most peripheral bin, showing a weak η dependence.
- A peak around $\Delta\phi = 0$, $\Delta\eta = 0$, very pronounced for most peripheral collisions, getting weaker towards more central events, and disappearing for

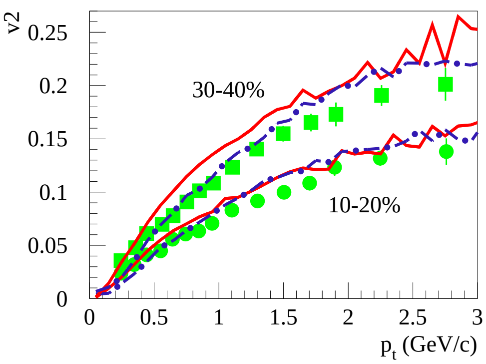

Figure **5**: (Color online) The transverse momentum dependence of v_2 for charged particles, compared to data (points), for two different centralities. We show the full calculation (solid line), and a calculation without hadronic cascade (dashed-dotted).

central collisions.

The $\cos(2\Delta\phi)$ component seems to be independent of η, so we can crosscheck the model by comparing with $v_2 = \langle\cos 2\phi\rangle$ measurements for $\eta = 0$ [13] at two different centralities: In fig. 5, we show the transverse momentum dependence of v_2.

The ridge contribution is most easily discussed for the highest centrality class (see fig. 4, 5-10%), where "the ridge" is the difference $R(\Delta\eta,\Delta\phi) - R(\Delta\eta,\pi)\cos 2\Delta\phi$. The reason for this correlation in our approach can be seen from figs. 1 and 2: individual events show typically (due to random fluctuations) a certain number of "hot spots" of very high energy density, elongated in longitudinal direction in the string model approach ($\rightarrow$ "hot tubes"). This leads to a squeeze-out of matter with high radial velocity at certain azimuthal angles ϕ_K, typically between the hot tubes. The effect get weaker towards more peripheral collisions, because the transverse area gets smaller, and there is finally only a single hot tube in the center, which will not produce any ridge structure.

The peak in the peripheral centrality class (see fig. 4, 80-90%) is in our model clearly identified as coming from jets. It should be said that at 2.76 TeV, in our model, all elementary interactions are hard (so sloppy spoken: everything comes from "jets"). The correspond elementary flux tubes are kinky strings, which are mainly longitudinally, but there are transversely moving parts, carrying the momenta of the hard scatterings (see ref. [6]). These strings are the basis for the calculation of the initial energy density, and of course very high momentum string segments have to excluded. We employ a somewhat modified procedure for bulk / jet separation compared to our earlier work, where all string segment with $p_t > p_t^{\rm cut}$ could escape unmodified. Here we have in mind a picture where the high transverse momentum string segments lose energy via the energy loss of the corresponding partons, and therefore the energy loss of the string segments moving a distance dL through space characterized by an energy density ε (from other strings) is given via the parton energy loss formula $\Delta E \propto \varepsilon^{3/8}\sqrt{E}dL$ [14]. For low transverse momentum segments, we use simply $\Delta E \propto \rho dL$, with ρ being the string density. In any case, segments with $E > \Delta E$ escape the plasma – which is also possible for low momentum segments, sitting on the surface of the matter distribution.

In this sense the peak in peripheral collisions is due to escaping jet elements. The peak disappears for more central collisions, because of an increase of the chance of hadronic rescattering of these low momentum jet elements with frozen out particles from the plasma.

In summary, untriggered two-dimensional di-hadron correlations provide interesting information about a multitude of dynamical features of the expanding plasma: the elliptical flow as a consequence of a global azimuthal asymmetry of the initial matter distribution; the ridge coming from initial density fluctuations, which lead to asymmetric radial squeeze out of matter; a peak from low momentum jet components, having survived the plasma – providing a link to the crucial question of separating bulk and the low momentum pieces of jets.

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